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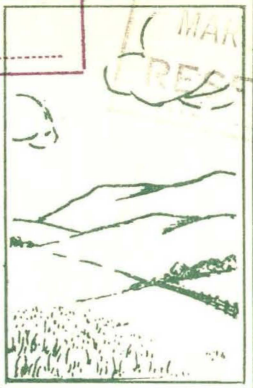

No. 47

December, 1947

THE SAN DIMAS LYSIMETERS:

...instruments for evaluating the water economy of chaparral vegetation...

Part I--The lysimeter installation and research program.

Part 2--The relative performance of four types of lysimeters.

By

E. A. Colman and E. L. Hamilton

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FOREWORD

A description of the San Dimas lysimeters would be incomplete without mention of the individuals, other than the authors, and of the organizations that took part in developing this installation.

The major features of the installation were based upon lysimeters originally designed by W. C. Lowdermilk in connection with earlier projects of the Experiment Station. Persons intimately concerned with the planning and construction were E. I. Kotok, C. J. Kraebel, J. D. Sinclair, W. U. Garstka, J. S. Cotton, H. F. Jerauld, H. G. Wilm, and P. B. Rowe, all at that time members of the California Forest and Range Experiment Station staff. Invaluable aid in a consulting capacity was rendered by E. N. Munns, Chief of the Division of Forest Influences Research of the Forest Service; by F. J. Veihmeyer, G. B. Bodman, and the late C. F. Shaw, all of the University of California; and by the late F. E. Clements of the Carnegie Institution of Washington. L. F. Reimann has been responsible for many mechanical developments that have facilitated the operation of the lysimeters. Construction of the whole installation was made possible by the assistance of men and materials provided by the Civilian Conservation Corps and the Work Projects Administration. Grateful acknowledgement is made at this time for the assistance that has been derived from these many sources.

PART I -- THE LYSIMETER INSTALLATION AND RESEARCH PROGRAM

The San Dimas Experimental Forest is a 17,000 acre watershed research laboratory situated in the San Gabriel Mountains of southern California. (4)[1/] Here the U. S. Forest Service is studying rainfall, soil water movement, streamflow, and erosion, in a research program planned to develop the principles and practices of management for chaparral-covered watersheds. The goal of such management is the maximum production of usable water combined with minimum flood and erosion danger. The lysimeter installation of the Experimental Forest was designed for the purpose of studying the influence of certain species of chaparral vegetation upon the disposition of precipitation reaching the soil. It thus forms an integral part of the watershed-management research program for which this experimental forest was established.

Vegetation must be considered in any plan of watershed management because of its very considerable influence upon runoff, erosion, and evaporative loss of soil water, and because of the possibilities of modifying this influence by cultural treatment. The role of vegetation in watershed management may be defined in terms of its water economy, which can be measured by the influence vegetation exerts upon infiltration and soil permeability, and by its evaporation-transpiration characteristics.

It is difficult to compare directly in the field the water economy of various kinds of vegetation because of soil variability and the limited experimental control over important factors possible under field conditions. Lysimeters make possible a high degree of experimental control over soil and environment so that vegetation can be isolated as the only important influencing factor. Despite some shortcomings which will be described presently, lysimeters are the most satisfactory instruments now available for comparing the water economy of different kinds of plants.

THE PROBLEM OF LYSIMETER DESIGN

The type of lysimeter to be employed in any study depends upon the particular objective of that study. The advantages and limitations of the several types of lysimeters have been clearly presented by Kohnke et al (3), but a brief resume here will indicate the reasons underlying the choice of those used in the San Dimas study.

1/ Numbers in parentheses refer to Literature Cited, page 14.

Lysimeters may be divided into three types: the Russian or Ebermeyer lysimeter, the "in place" or "core cutter," and the "filled" type, which is filled with soil after construction.

The Ebermeyer type consists merely of a percolate-collecting funnel buried in natural soil. It imposes no restrictions upon surface runoff or root development since it has no confining walls. Capillary forces operating in the soil surrounding the funnel cause some of the percolating water to pass around the funnel rather than into it. Because it does not intercept all the water that penetrates to the level of the funnel, it is unsatisfactory for the quantitative measurement of water seepage.

The "in place" lysimeter consists of an impervious shell (metal, concrete, or wood) placed around and under a block of undisturbed soil. By this operation the soil block is completely isolated, and collection of all surface runoff and seepage is assured. The increase in experimental control thus accomplished is accompanied by a significant departure from natural conditions, for the soil/air interface across which seepage water must pass to leave the soil results in the establishment of a saturated soil layer covering the bottom of the lysimeter during the seepage period. Seepage cannot take place unless the water-absorptive power of the soil immediately above the seepage plane has been satisfied. This condition is met only when the soil there is virtually saturated with water, which, in turn, means that a nearly saturated condition exists for some distance above this plane. The thickness of the layer of abnormally wet soil increases with increasing fineness of soil texture. The presence of this "perched water table" is characteristic of enclosed lysimeters as a group. In some "in place" lysimeters, such as those at Coshocton (6), the seepage plane is located at such a depth that a natural soil profile extending well into the parent rock has been enclosed. Such an enclosed soil block probably exhibits more **nearly natural** conditions than would be the case if soil rested directly on the seepage plane.

"In place" lysimeters, including as they do an undisturbed block of natural soil, are in many instances the most desirable type. However, when they are installed in soils that are not uniform, many replications must be made in order to establish the significance of results obtained from them. The "in place" lysimeter is used to best advantage for studies in which the soil itself is the variable under investigation.

For studies in which vegetation or treatment of the soil surface are the prime variables, the experimental error of the study should be decreased by minimizing soil differences. Here a filled-type lysimeter is indicated, and within this type there still remains room for choice. The lysimeter shell can be filled with soil mixed by layers or with soil homogenized through its entire depth. This choice is again dependent upon the study for which the lysimeter has been designed.

Because the San Dimas lysimeters were installed to compare the water-use and water-yield characteristics of several species of chaparral plants, it was necessary in this installation to combine maximum control over environmental and soil variables and minimum interference with natural growing conditions for the vegetation. For this reason all the lysimeters are of the filled-type, employing homogenized soil, and so located as to be subjected to uniform environmental conditions.

The San Dimas lysimeter installation (fig. 1) consists of five types of lysimeters all located within a rodent- and deer-proof enclosure about 2 acres in area. Uniformity of topography has been emphasized in the location, and all facilitating equipment is so placed as to offer minimum interference to the above-ground environment. A climatic station within the area is equipped to measure all meteorological variables that are suspected of having an influence upon the study. The several groups of lysimeters are surrounded by buffer areas. Lysimeters and their buffer areas receive the same treatment so that the lysimeters, in effect, are sampling areas of uniform treatment. This prevents the border plants from affecting the measured lysimeters themselves.

THE LARGE LYSIMETERS

The large lysimeters form the master group, the others having been installed either to get measurements that could not be made in the large ones or to aid in the application of lysimeter results to natural field conditions. The large lysimeters (figs. 2 and 3) are 26 contiguous concrete tanks, each 10.5 feet by 20.8 feet in horizontal dimensions and 6 feet deep. Each lysimeter holds approximately 64 tons, dry weight, of uniformly mixed stock soil. All concrete surfaces have been coated with a waterproof phenolic resin paint to minimize reaction between the concrete and the plant roots or soil. Each lysimeter has a surface and bottom slope of 5 percent on its long axis, enough to insure adequate surface drainage without introducing slope as a factor in the study. Metal troughs cover the walls between adjacent lysimeters. These troughs can be used to measure the rain falling through the vegetation crowns, that is: rain less interception and stemflow. Surface runoff is collected in a trough extending across the lower end of the soil surface, while seepage drains from the soil through a perforated plate that lies across the lower edge of the soil block. Rain, runoff, and seepage are measured separately for each lysimeter in collector tanks located in a tunnel adjacent to the lysimeter line. Water stage transmitters (1) mounted on the collector tanks in the tunnels are connected to strip-chart recorders which record the rates of rain, runoff, and seepage. This automatic recording is important, for rate measurements are more valuable than measurements of volume in any study involving soil-moisture movement.

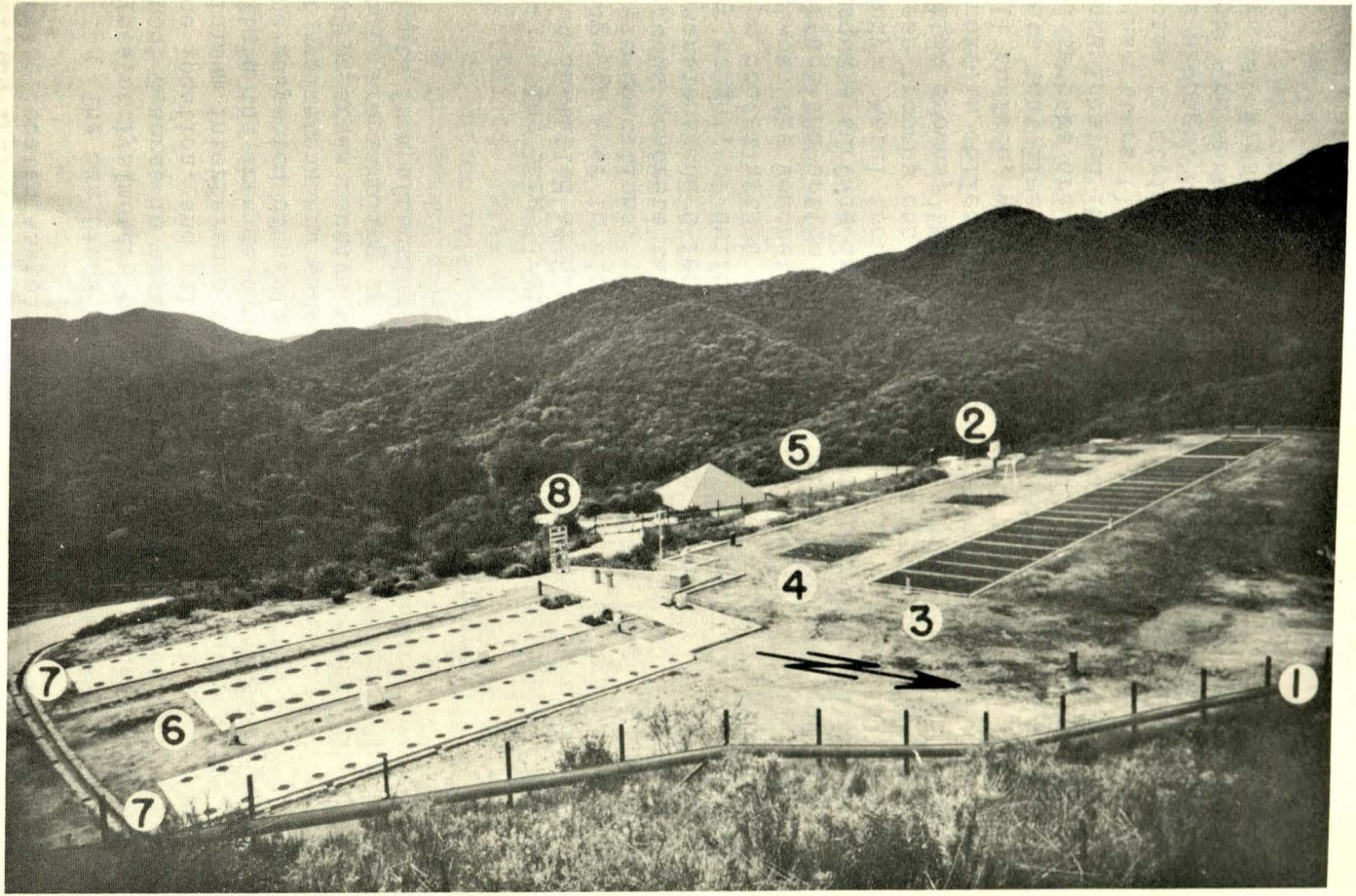

Figure 1.—The San Dimas lysimeter installation. 1. Rodent-and deer-proof fence; 2. climatic station; 3. line of large lysimeters; 4. line of "unconfined lysimeters"; 5. line of root study lysimeters; 6. lines of medium weighing lysimeters; 7. lines of small weighing lysimeters; 8. weighing crane.

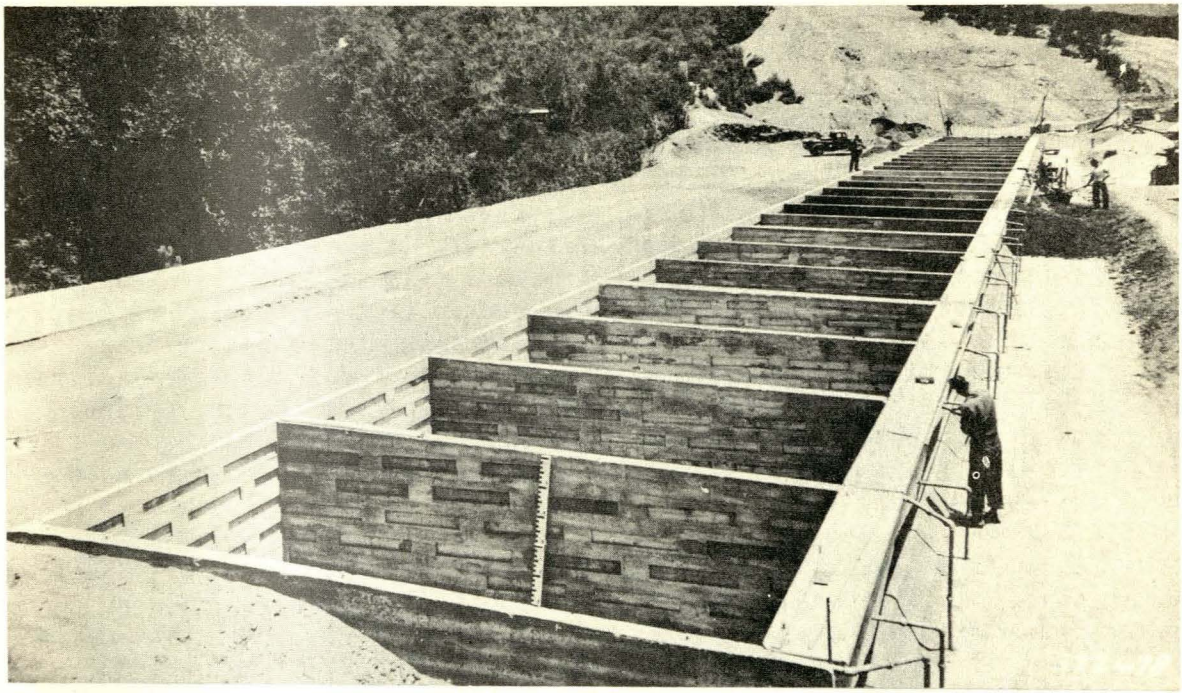

Figure 2.—The large lysimeters before filling. Rain and runoff pipes are shown leading into roof of collector tunnel.

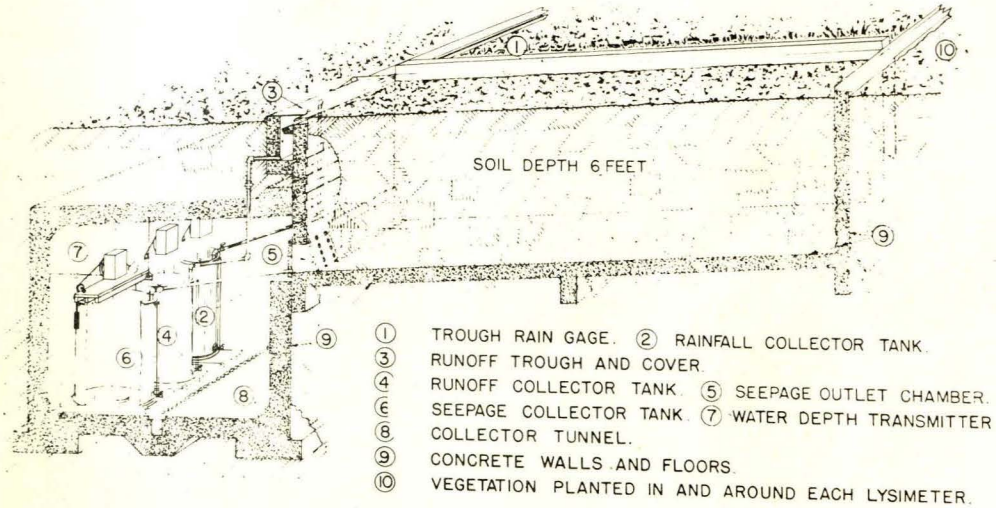
SOIL DEPTH 6 FEET
① TROUGH RAIN GAGE. ② RAINFALL COLLECTOR TANK.
③ RUNOFF TROUGH AND COVER.
④ RUNOFF COLLECTOR TANK. ⑤ SEEPAGE OUTLET CHAMBER.
⑥ SEEPAGE COLLECTOR TANK. ⑦ WATER DEPTH TRANSMITTER
⑧ COLLECTOR TUNNEL.
⑨ CONCRETE WALLS AND FLOORS.
⑩ VEGETATION PLANTED IN AND AROUND EACH LYSIMETER.

Figure 3.—Diagram of a single large lysimeter. Surface area 5 milacres (10½ by 21 feet).

THE MEDIUM AND SMALL LYSIMETERS

The large lysimeters provide absolute control of surface runoff, seepage, and root distribution, on a scale large enough to permit a close approximation of natural plant-growth conditions. They were not designed, however, for the direct measurement of evaporation and transpiration. For this purpose two types of cylindrical, galvanized-iron lysimeters were installed. Of these the medium lysimeters, holding an average of 1600 pounds of soil (fig. 4), have a surface area of 750 square inches and are 40 inches deep. They are large enough to support small groups of plants. The small lysimeters (fig. 5) hold an average of 320 pounds of soil, are 250 square inches in area and 24 inches deep. They were intended for measurement of the water use of single plants grown under artifically controlled soil moisture conditions. Lysimeters of both types rest on pedestals placed in the bottom of concrete-lined trenches so that the soil surfaces of the lysimeters are exposed at ground level. The spaces between the lysimeters are covered with wooden collars, leaving only the soil surfaces exposed to the atmosphere.

The medium lysimeters are equipped for the measurement of runoff and seepage, but the small lysimeters are not. Periodic weighing of both medium and small lysimeters is accomplished by use of a crane scale hung from a wheeled derrick. Evaporation and transpiration losses of soil water can be calculated from repeated weighings.

Thirty medium and seventy-two small lysimeters have been constructed, so that ample replications can be made of plant species growing in the large lysimeters.

THE UNCONFINED LYSIMETERS

As a result of the artifical environment imposed upon plants confined in lysimeters, some transition is needed between enclosed blocks of soil and natural soil conditions in the field. This requires the determination of a relation between the water economy of plants growing in confined blocks of uniform soil and that of the same plants growing in the same kind of soil with the confining walls removed. To accomplish this five pits, each $17\frac{1}{2}$ feet square and 7 feet deep, were dug just south of the large lysimeter line. All pits were refilled with stock lysimeter soil. On the surface of each refilled pit was laid out a sheet-metal-bordered plot from which surface runoff can be collected and measured. Each plot is 7.5 feet wide and 14.6 feet long. The upper and lateral edges of the plot are formed of half-buried strips of 12-inch-wide galvanized iron. A galvanized iron trough laid across the lower end intercepts surface runoff, which is then conducted to a collector tank. Water-stage transmitters provide measurements of runoff rates.

Each block of soil thus equipped is called an unconfined lysimeter (fig. 7). The soil from which measurements are taken is surrounded on sides and bottom by the same kind of soil. The depth of the unconfined lysimeter soil is considered to be 6 feet, so that a 1-foot thick soil layer lies beneath it.

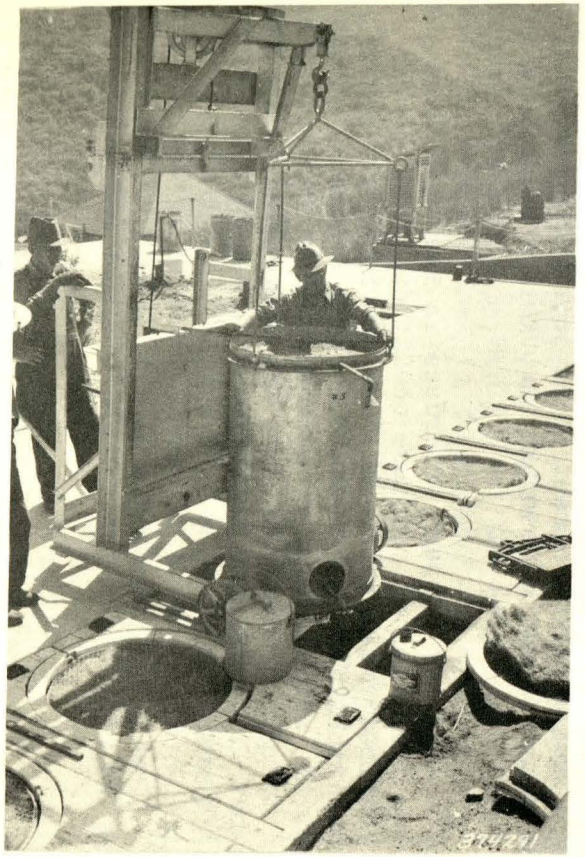

Figure 4.—Medium lysimeters, suspended on weighing crane and in trench. Seepage and runoff collector tanks and weighing scale alsoshown. Excelsior mats protect the soil surface from erosion.

Figure 5.—Small lysimeter hanging on weighing crane.

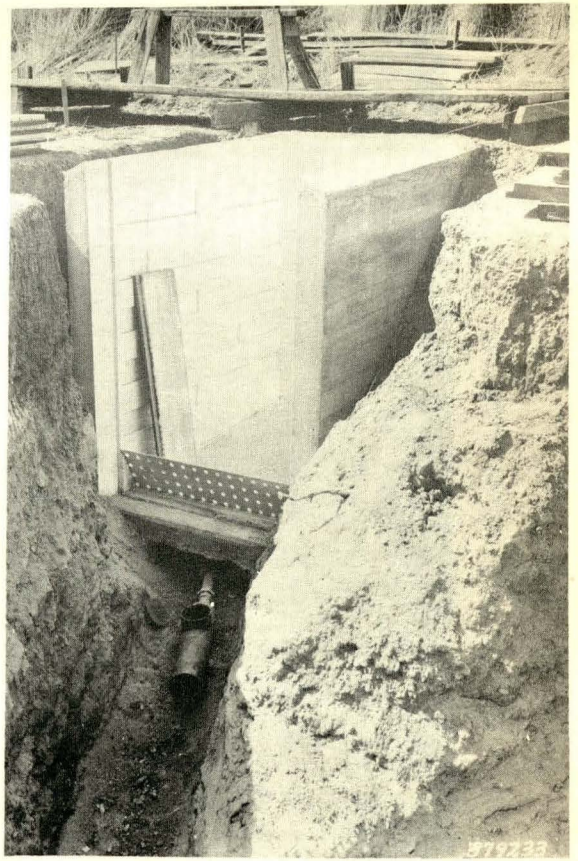

Figure 6.—Unfilled root-study lysimeter with plank wall removed. Perforated metal seepage plate and seepage pipe shown at bottom of lysimeter.

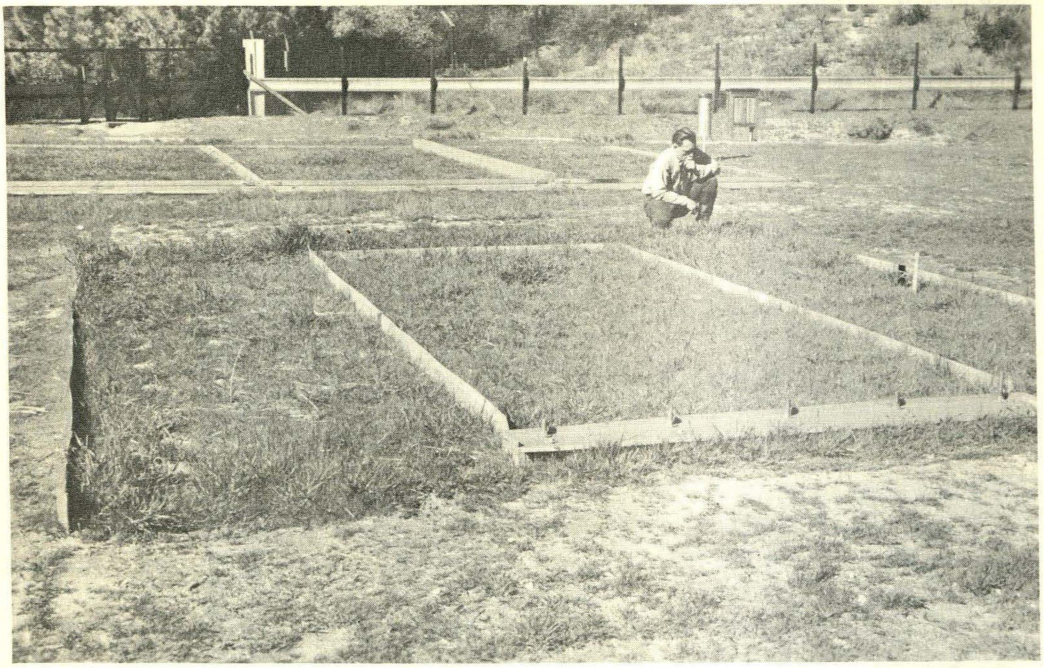

Figure 7.--Surface of an "unconfined lysimeter" showing runoff plot placed within border strip of filled soil.

No direct measurement of seepage through the "bottom" of this type of lysimeter can be made but there are instruments by which the amount and rate of seepage can be calculated. Richards, Russell, and Neal (5) have demonstrated the usefulness of tensiometers for indicating the direction of water movement in the soil. One unconfined lysimeter has been equipped with tensiometers which are serving satisfactorily as seepage detectors. Periodic soil moisture sampling, coupled with tensiometer measurements that show the direction of soil water movement, can be used to calculate the amount of seepage through the unconfined soil blocks.

The lack of a soil/air seepage interface in the unconfined lysimeter eliminates the abnormal moisture conditions found in the deeper levels of confined lysimeters, and thus provides more nearly natural growing conditions for the vegetation being studied. At the same time, however, the substitution of calculated for measured seepage and the impossibility of confining roots to the controlled soil block will detract somewhat from accurate measurement of vegetation water economy in these lysimeters.

THE ROOT-STUDY LYSIMETERS

The root distribution of plants grown in enclosed soil blocks is to be studied in five specially designed lysimeters. These root-study lysimeters are concrete boxes, similar in shape and slope to the large lysimeters (fig. 6). Their soil depth is 6 feet, identical with that in the large lysimeters, but in horizontal dimensions they are only 4 by 6 feet. Their lower end walls are made of redwood planks, fitted so that they can be removed for observation of soil and roots. These lysimeters are not equipped for measurement of runoff or seepage, but as will be noted in the photograph, seepage water is caused to drain from the soil blocks through a perforated plate similar to that used in the large lysimeter. For this reason soil moisture conditions in them should be like those in the large lysimeters. The measurements planned for these lysimeters are related only to plant growth. After plants have grown in them for a sufficient length of time the redwood walls will be removed and the soil washed out, exposing the plant roots for detailed study of their distribution.

THE LYSIMETER SOIL

All lysimeters of the San Dimas installation have been filled with the same kind of soil: a reddish sandy clay loam developed residually at the lysimeter site from dioritic rock of the San Gabriel formation. This soil is probably rather closely related to the Fallbrook soil series. It is similar to soils found elsewhere within the San Dimas Forest on relatively flat areas which have been little dissected in the present erosion cycle. At the lysimeter site it is present in depths exceeding six feet.

Prior to excavation the lysimeter soil showed only a week tendency toward profile development. Its clay content increased slightly to a depth of about 12 inches and then decreased progressively with greater depth. This was reflected in its moisture equivalent, which increased from 18.3 percent in the top 3 inches to 19.1 percent at one foot depth, and then dropped to 15.1 percent at five feet. Apparent soil density increased somewhat with depth, but the only significant difference was between the surface foot (1.4 gm./cc.) and the average of the next four (1.6 gm./cc.)

Soil used to fill the lysimeters was excavated from the site of the large lysimeters and the tunnel. Some 2800 cubic yards taken from the top six feet of this excavation was mixed as thoroughly as possible, passed air-dry through a 3/4-inch screen, and then stored in a bin prepared for this purpose. As the soil was placed for storage, every effort was made to remove all traces of textural variation. The success of the mixing was tested by determining the mechanical analysis of 100 soil samples taken at random from all parts of the storage bin. According to this analysis the soil contained, on the average, 60 percent sand,

25 percent silt, and 15 percent clay. Statistical analysis showed that no significant textural differences existed anywhere in the storage bin. The moisture equivalent of the mixed soil was found to be 19 percent, and the wilting point, 7 percent. Later field tests showed that its field capacity was about 18 percent.

Preliminary experiments in placing and settling the soil were made in walled-off portions of several large lysimeters in order to develop a soil-placement method that would insure the greatest uniformity in density as well as maintain the other already-uniform characteristics of the soil. Several methods of placing and tamping were tried, and analyses were made of the distribution of apparent soil density throughout the resulting soil blocks. The method selected showed a standard deviation of only $\pm$ .03 of 1 percent of the average apparent density throughout any one soil block and no significant relation of apparent density to depth. This method consisted of filling the lysimeters by 3-inch-thick soil layers. After sufficient soil was dumped into each lysimeter to consitute a layer, the soil was spread evenly, and then its entire surface was chopped through with a flat-bladed spade. The chopping jarred the soil into close aggregation without introducing the compression zones that usually result from the use of blunt tamping tools.

The success of the soil-placement method is shown by the results of filling the large lysimeters. All soil going into the lysimeters was weighed and sampled for moisture so that the dry weight of each lysimeter soil block could be calculated. At the time they were filled, the average dry weight of soil in the 26 large lysimeters was 137,379 pounds, the standard deviation was only one-half of one percent of this weight, and the extreme range in weight was less than 2 percent. This placed the mean apparent density of soil in the large lysimeters at 1.44 gm/cc. at the time of filling.

The soil in the pits which hold the unconfined lysimeters, likewise, was satisfyingly uniform. Although each of these pits contains nearly twice as much soil as a large lysimeter, their average apparent density was 1.45 gm/cc. at the time of filling; the range of density through the 5 soil blocks was less than 2 percent. The soil in the pits of the unconfined lysimeters is therefore considered to be the same, in all respects, as that in the large lysimeters.

The large and unconfined lysimeters were over-filled 12 inches in order to allow for soil settling during the first few years of exposure to the elements. Annual surveys of the soil surfaces showed that 70 percent of the total settling took place during the first year of exposure; that is, as a result of the first wetting and drying of the soil blocks. By 1940, three years after their first exposure, settling had decreased to a negligible amount. The average settling up to this time had totaled about 6 inches. In the fall of 1940, therefore, the remaining overfill soil was removed and the final lysimeter depth of 6 feet

was established. At this time the average dry weight of soil in the large lysimeters was found to be 127,191 pounds, and that of the pits of the unconfined lysimeters, 206,012 pounds. This established their average apparent densities at 1.57 and 1.55 gm/cc., respectively. Soil settling had brought about an increase in apparent soil density of 8.3 percent over the three-year period.

The medium and small lysimeters were filled with soil to the level of their runoff lips, using the procedure described above. In 1940 enough fresh soil was added to compensate for settling and to bring their soil surfaces once more to this level. The root-study lysimeters were filled in the same manner as the large ones. Their soil depths were also adjusted to 6 feet in 1940.

EVAPORATION AND TRANSPIRATION MEASUREMENTS

The measurement of runoff and seepage leaves one phase of the water cycle measured only indirectly in the large and "unconfined" lysimeters. This is the evaporation-transpiration water losses which were to be determined by repeated weighings of the medium and small lysimeters, as has already been explained. Early in the lysimeter study it appeared desirable to study methods of making these measurements directly in the large and "unconfined" lysimeters instead of assuming some relationship to exist between the stationary and the weighed types. Accordingly, periodic soil-moisture sampling was carried on for several years in two of the large and in one of the "unconfined" lysimeters. Despite the desirability of sampling more lysimeters, the large amount of work required and the possibility that sampling might alter lysimeter characteristics has prevented further expansion. The need for some "in situ" soil-moisture indicator stimulated research into the development of an electrical soil-moisture meter. An instrument has been developed on the Experimental Forest which may provide a solution to this problem (2). Soil and measuring units of this instrument were manufactured in 1947, and a test installation in the lysimeters is planned for 1948.

THE LYSIMETER RESEARCH PROGRAM

The research plan for the lysimeters includes three periods of study. During the first period, 1937-40, the soil surfaces were maintained free of vegetation and protected from erosion by a mulch of excelsior. Measurements of rain, runoff, and seepage were made, so that inconsistencies in reaction between the several lysimeters of each type could be discerned. The principal purpose of this preliminary period, however, was to permit the completion of soil settling.

After the removal of surplus soil from the lysimeters in 1940, an annual grass (Bromus mollis) was planted to start the second research period. The use of this species, which has considerable importance in the range lands of central California, was to have a twofold purpose: (1) it would provide an opportunity to detect consistent or erratic differences between lysimeters under a vegetation made as uniform as possible, and (2) information would be obtained relative to the life cycle of the grass and its water economy. After the first seeding, the grass was allowed to seed itself naturally both inside the lysimeters and in the border strips around them.

During the grass-cover period one of the large lysimeters and four each of the medium and small tanks were maintained bare of all vegetation. This made possible a comparison of the water regime under bare and under grass-covered surfaces. There was a highly significant difference in erosion between the two treatments on the large lysimeters. The bare soil developed an erosion pavement and suffered a considerable loss of fine material, while the dense grass cover on the planted lysimeters prevented erosion almost completely. The infiltration rate of the grass-covered lysimeters increased since the first seeding by a small but significant amount, while that of the bare large one remained at the very low value which characterized all the lysimeters during the preliminary, excelsior-surfaced period.

The final research period started in 1946, when the grass cover was replaced by the chaparral species whose water economy the lysimeters were planned to measure. The planting plan of the lysimeters is presented in Table 1. Five species of native chaparral plants have been used: Eriogonum fasiculatum, Adenostoma fasiculatum, Ceanothus crassifolius, Quercus dumosa, and Pinus coulteri. A single planting of each species occupies five contiguous large lysimeters, one unconfined lysimeter, and the buffer areas around them, which extend 20 feet north and 50 feet south of the edges of the large lysimeter line. One of the large lysimeters is still maintained with a bare soil surface.

The root study lysimeters and their buffer area have also been planted, one to each of the study species. The medium and small lysimeters remain unplanted in 1947. As is reported in Part 2 of this paper, inconsistencies in reaction have been observed between the weighing-type lysimeters and the others. Until certain changes in design have been made in them the medium and small lysimeters will remain withdrawn from use in the lysimeter study.

Table 1.- Planting plan of San Dimas lysimeters

Large lysimeter No.	Species		Unconfined lysimeter No.
1	Bare		
2	Eriogonum fasiculatum	(border)	
3,4,5	" "	(controlled)	A
6	" "	(border)	
7	Adenostoma fasiculatum	(border)	
8, 9, 10	" "	(controlled)	B
11	" "	(border)	
12	Ceanothus crassifolius	(border)	
13, 14, 15	" "	(controlled)	C
16	" "	(border)	
17	Quercus dumosa	(border)	
18, 19, 20	" "	(controlled)	D
21	" "	(border)	
22	Pinus coulteri	(border)	
23, 24, 25, 26	" "	(controlled)	E

SUMMARY

The San Dimas lysimeters were established for the purpose of comparing the water economy of a number of chaparral plant species that are important in the management of southern California mountain watersheds. The installation includes five types of lysimeters and a climatic station located on an area of uniform topography and enclosed in a rodent-proof and deer-proof fence. The same kind of soil has been used and uniformly placed in all the lysimeters in order to minimize soil variability. Rain, runoff, and seepage are measured, and weighing or periodic soil moisture sampling is used to study evaporative water losses.

The lysimeters were installed in 1937 and their soil settling was measured under excelsior-covered surfaces from 1937 to 1940. In 1940 the originally overfilled soil blocks were cut down to their final depths and all but a few tanks were seeded with Bromus mollis, thus initiating the second phase of the study. The final phase of research was entered in 1946 with the conversion of the grass cover to stands of the several chaparral species whose water economy is to be studied.

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PART 2 -- THE RELATIVE PERFORMANCE OF FOUR TYPES OF LYSIMETERS[1/]

The purpose of this paper is to compare certain data obtained from four types of lysimeters included in the San Dimas installation, to learn whether it is possible to use one type of lysimeter to provide data to supplement those obtained in another type.

A number of investigators have suggested that simple or even consistent relations might not exist between the moisture conditions of different kinds of lysimeters. In 1913 Willard and Humbard (10)[2/] noted that more water passed through a four-foot depth of undisturbed field soil than through a lysimeter having the same soil depth and treatment. In 1917 Alway and McDole (2) found that a fine soil underlain by sand retained more water against drainage than it did when this textural layering was not present. These studies introduced the concept of the interface effect: the incomplete drainage of enclosed lysimeters caused by the requirement that seepage water must pass across a soil-over-air interface in order to leave the soil. Aderkas (1) found that shallow lysimeters filled with sand held more water per unit of depth than did deeper ones. This he attributed to the interface effect and he noted that, as a result, increased evaporation corresponded with a decrease in lysimeter soil depth. Neal, Richards, and Russell (7) buried tensiometers in confined lysimeters and found that the soil in the bottom of the lysimeter must be nearly saturated before seepage would occur.

Most early investigators who made use of lysimeters expressed no concern over the reliability or applicability of their data. The literature shows that these workers almost always assumed that their lysimeters represented an approach sufficiently close to natural conditions to satisfy them, at least with respect to the factors under investigation. Recently, however, there have been suggestions that moisture conditions in enclosed soil blocks might be sufficiently different from conditions in the field to justify a critical examination of the lysimeters themselves. Thus Wallihan (9) studied the influence of the soil/air seepage interface by inserting a tensiometer cup in the base of a small lysimeter and maintaining a tension of 10 cm. Hg on the soil water at that level. He found significant differences in evaporation, seepage, and plant growth between this lysimeter and one in which no seepage tension was applied. In their excellent survey of lysimeters, Kohnke, Dreibelbis, and Davidson (6) stress the importance of duplicating natural environmental conditions in enclosed soil blocks if the data obtained from them are to have field application. They mention the desirability of measuring, not only the average moisture content of the lysimeter soil, but also the distribution of moisture within the soil block.

1/ The graphical analysis included in this paper was performed by N. O. Broughton of Civilian Public Service Camp #76, Glendora, California, whose assistance is gratefully acknowledged.

2/ Numbers in parentheses refer to References, page 33.

In 1940 and 1941 the American Geophysical Union Committee on Evaporation and Transpiration devoted its annual reports (4, 5) almost exclusively to discussions of the usefulness of water utilization data obtained from lysimeters. Although many excellent discussions and suggestions appear in these reports, there is a marked lack of reference to specific studies of lysimeter behavior. Most of the discussions suggest that lysimeters do not provide data comparable with those obtained from natural soils, and both reports emphasize the necessity for establishing natural conditions in lysimeters before comparable results can be obtained. Summarizing the replies to the questionnaire which formed the basis of the 1941 report Kittredge stated: "the point is emphasized by several that the transpiration from plants in containers would be the same as that without, if all the conditions and particularly the soil moisture, were the same within as without ... If the conditions are not thus identical, the application of figures for estimation of transpiration over large areas forthwith becomes subject to uncertainty."

The wide response to the lysimeter questionnaires indicates the interest shown by research men in the problems connected with their use. The lack of unanimity upon many points demonstrates the need for studies designed specifically to investigate the behavior of lysimeters. The San Dimas lysimeter installation provides an opportunity for such a study since it includes several lysimeter types differing in design but identical as to environment, soil, and vegetation. Information concerning this installation was presented in Part 1.

THE DATA

Since the lysimeters of the San Dimas installation were designed to study the water economy of plants, a comparison of water content of the several lysimeter types was made the primary basis for the study of their behavior.

The small and medium lysimeters were weighed weekly during the greater part of each year, thus providing direct periodic measures of their water content. From 1937 to 1940 all 72 small and all 30 medium lysimeters were maintained free of vegetation. After 1940 four tanks of each type were kept bare while the remainder supported reasonably uniform stands of annual grass (Bromus mollis). The soil water contents used in this analysis are average values for each date of determination, for all lysimeters having the same treatment. Soil samples were obtained twice during the course of this study from each set of the weighing lysimeters. Soil was collected by 3-inch layers so that its moisture content could be related to soil depth and lysimeter treatment.

The large and unconfined lysimeters received the same sequence of treatments as did those just described. All the unconfined and all but one of the large lysimeters were planted to Bromus mollis in 1940. The remaining large lysimeter was maintained bare of vegetation throughout this period.

The water content of the large and unconfined lysimeters was determined by periodic moisture sampling during the last two years of this study. Weekly or bi-weekly samplings were made in one bare and one grass-covered large tank and in one of the grass-covered unconfined lysimeters. Soil water content was determined by 6-inch-thick soil layers to a depth of 6 feet. Total water contents of the lysimeters were calculated from these data for each date of sampling.

The grass yields of all the lysimeters were determined each year after the matured grass was mowed to a uniform stubble height. The dry weight of the grass produced in 1940-41 and 1941-42 in the four types of lysimeters has been utilized to show further the agreement between lysimeter groups.

In analyzing the soil-moisture data the most direct comparisons have been made possible by plotting the average water content of one lysimeter type against that of another type on the same day. By this procedure definite relations demonstrated themselves readily, the general shape of the data envelopes indicated the kind of relation existing between the two variables, and the scatter of the data about the regression line provided an indication of the reliability of the relation. Furthermore, when the plotted data were connected in chronological sequence the relation between corresponding periods or moisture stages could be studied.

Statistical analysis has not been resorted to in this study because the results are believed to be sufficiently well defined without the use of mathematical criteria of reliability. Instead, in those cases showing definite relations the regression line has been used as the means of calculating the water content of one lysimeter type from that of the other. The calculated and measured values have then been plotted on the same chart as a function of time; and the occurrence, magnitude, and direction of differences between the two were studied to indicate the significance of the regression line.

RESULTS OF ANALYSIS

Relation between water content of medium and small lysimeters.

In figure 8 data are presented relating the water contents of the medium and small lysimeters. In Figure 8(A) the average water content of the bare lysimeters has been plotted for the period from March 1938 to October 1942. In Figure 8(B) the same data have been plotted for the grass-covered lysimeters for the period October 1940 to October 1942. The relation in both cases is obviously linear, and the scatter of points is small enough to make the location of the regression line quite definite. Only in the early part of the 1940-41 season (indicated by lines connecting points) do the data show a distinct divergence from the general relation. At the start of this season fresh soil was added to all the lysimeters to make up for the soil settling that had taken place since the tanks were first filled. It is felt that the addition of dry

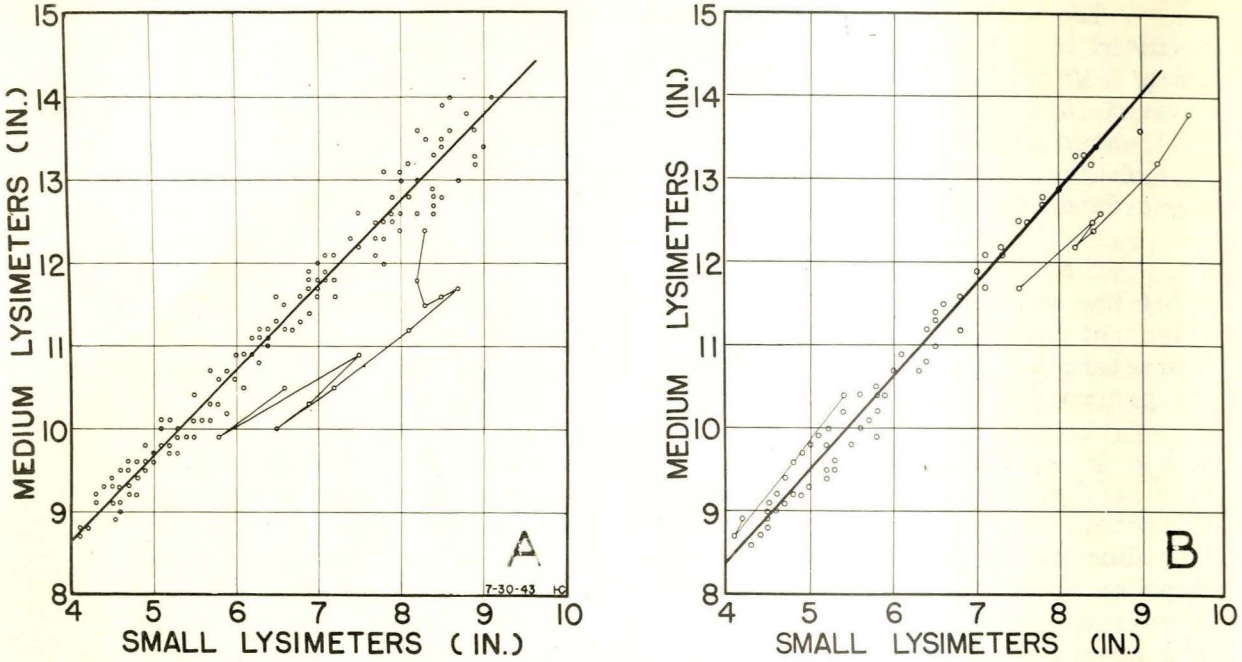


Figure 8.—Relation between water content of medium and small lysimeters; (A) bare soil, 1938-42, (B) grass-covered soil, 1940-42. (Early 1940-41 season data connected by lines.)

soil provided the cause of this divergence. The deeper medium lysimeters required, of course, more soil than did the smaller ones. The following equations describe the regression lines of Figures 8(A) and 8(B):

Bare lysimeters: $M = 1.03S + 4.53$

Grass-covered lysimeters: $M = 1.13S + 3.83$

In these equations M is the water content (inches depth) of the medium and S that of the small lysimeters.

It is apparent that water content is not directly related to soil depth, but that a proportionality factor must also be introduced. It will be noted further that the two equations, one relating bare and the other grass-covered lysimeters, have different constants. This indicates that treatment has an effect on the relative performance of lysimeters of different size and shows that the small lysimeters cannot be considered scale models of the medium ones. Therefore, it is not possible to calculate water use by plants in the medium lysimeters from water use measured in the small lysimeters without first growing the SAME PLANTS IN BOTH LYSIMETERS for a calibration period.

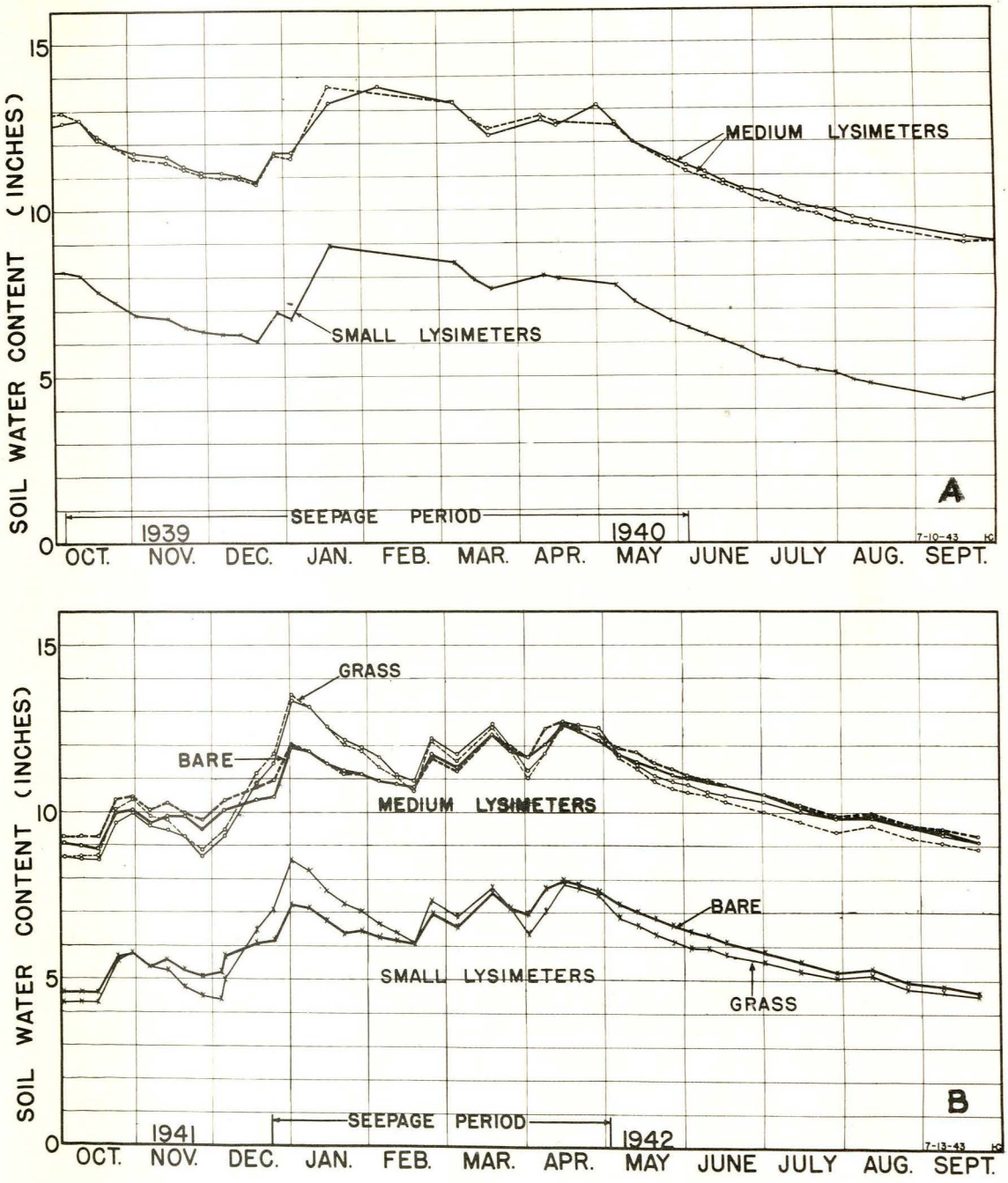


Figure 9.—Annual cycles of soil water content in medium and small lysimeters; (A) 1939-40, (B) 1941-42. Solid lines connect observed points; dashed lines, calculated points. (The same relations are shown during the 1940-41 and 1942-43 seasons.)

In Figure 9 the average measured water contents of the medium and small lysimeters are shown as a function of time for two years of the study. The figure also contains the water-content curve calculated for the medium lysimeters from the equations just presented. The general agreement of calculated and measured values for the medium lysimeters is immediately apparent. Considering the whole period of study, the maximum differences between calculated and measured values are found in the early part of the 1940-41 season, soon after the addition of fresh soil to the lysimeters. The reason for this difference has already been explained. With the exception of this period, the maximum difference is not greater than + .3 inch.

It will be noted in Figure 9 that each year the medium lysimeters (both bare and grass-covered) reached their maximum water content at very nearly the same date as did the small ones. During the following period of 3 or 4 months the average water-content of the medium lysimeters was 1.57 times that of the small ones. This corresponds very closely to the ratio of medium to small lysimeters soil depths (1.58 to 1) and thus indicates close agreement between the average maximum moisture contents of the two lysimeter groups.

The average water-content ratio in late summer was 1.98 to 1, showing that more water was lost in the drying period from the small (shorter) lysimeters relative to their depth than from the medium lysimeters. As is shown in Table 2 dry season water losses from the two lysimeter groups were nearly equal. This means that, depth for depth, the small lysimeters lost more water than did the medium lysimeters and, therefore, should have ended the dry season with a lower average soil-moisture content. This has been confirmed by measurement. Soil moisture samples were obtained late in September (the end of the dry season) from the medium and small lysimeters (fig. 10). As was expected the moisture contents of the small lysimeters were lower than those of the medium lysimeters at every depth under both bare and grass-covered surfaces. In view of these findings a consistent relation between the water contents of the two lysimeter groups would seem to depend on both groups being brought to maximum moisture contents (i.e., the establishment of seepage) each year. Because of their shallow depths and the possibility of impounding water upon their surfaces, this condition has been met each year despite a considerable variation in annual rainfall.

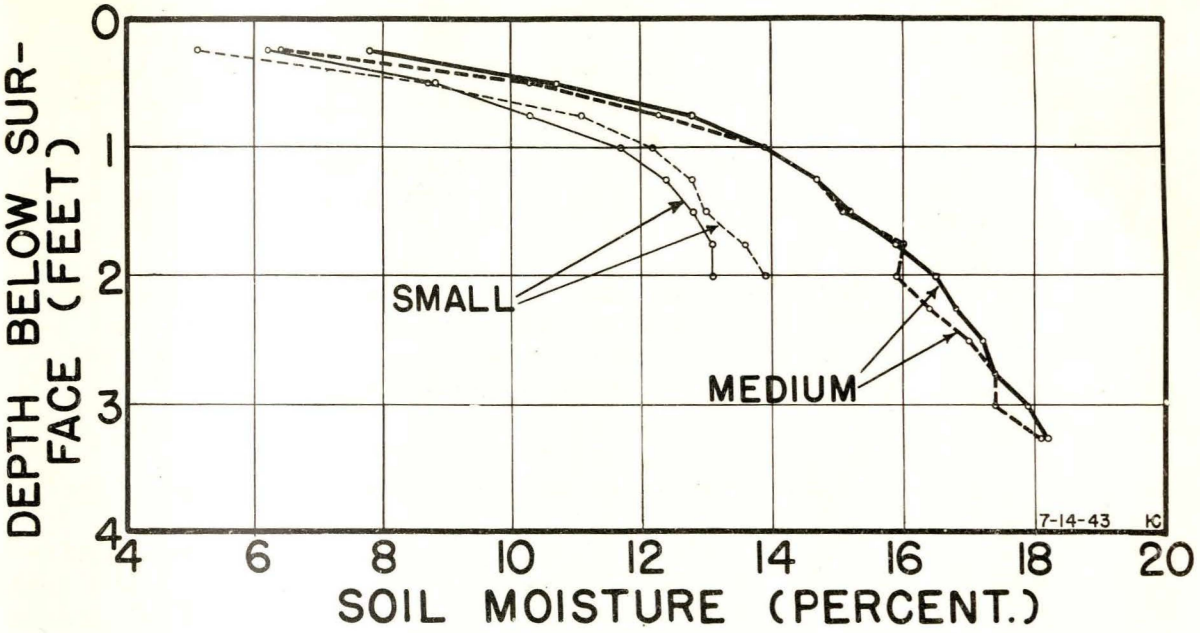


Figure 10.—Soil moisture distribution in medium and small lysimeters at the end of the 1940-41 dry season (9/25/41). Bare lysimeters shown by solid lines, grass-covered by dashed lines.

Table 2.- Dry season water losses from medium and small lysimeters

Year	Season	Evaporation (bare soil): Medium lysimeters	Evaporation (bare soil): Small lysimeters	Evapotranspiration (grass-covered soil): Medium lysimeters	Evapotranspiration (grass-covered soil): Small lysimeters
		Inches	Inches	Inches	Inches
1938	5/5 -9/28	4.0	4.0	-	-
1939	4/1 -9/20	5.3	4.9	-	-
1940	5/1 -9/14	4.0	3.7	-	-
1941	4/18-9/25	3.6	3.7	4.9	4.2
1942	4/15-9/22	3.5	3.2	3.6	3.3

Relation between water content of large and medium lysimeters maintained bare of vegetation.

Water content data for the total soil depths of the one bare large lysimeter and the average of the bare medium lysimeters over a period of two years have been related in Figure 11. The regression lines fitted to the data show better agreement between water contents of the two lysimeter groups during the dry part of each year than during the rainy part.

It will be observed first that data of the two years do not coincide. The two regression lines are parallel and both lie at such a slope that the coefficient in each equation is unity. The equations relating water content of the lysimeters are as follows:

1940-41 season: Large = medium + 9.41 inches
1941-42 season: Large = medium + 8.05 inches

The significance of the 45° slope of the two lines is not clear in view of the lack of such a relationship between the medium and small lysimeters. The separation of the lines representing the two years may be related to the rainfall characteristics of the two seasons. The 1940-41 rainy season was characterized by a long period of fairly continuous rain and a high seasonal total of 48 inches. The next year was characterized by scattered small showers totaling only 16 inches. In 1940-41 little evaporation occurred during the rainy season, and the rain was sufficient to produce seepage from both lysimeters. During the 1941-42 season most of the added water had been lost by evaporation before the end of the wet season, and soil sampling in the large lysimeters showed no water penetrating more than one foot below the surface. Therefore in the spring of 1941 the bare large lysimeter entered the dry season with a higher water content than it did the following year. The medium lysimeters, on the other hand, produced seepage both years. This was due to the impounding of water on their soil surfaces (the surface runoff outlet cannot be adjusted to drain the soil surface completely), which resulted in greater uptake of water in these lysimeters during the 1941-42 season than in the large lysimeters. The bare medium lysimeters reached very nearly the same maximum water content in both seasons, although this was not the case in the bare large lysimeter (fig. 11(A)).

The data in Figure 11(A) have been connected in chronological sequence, demonstrating the wide discrepancy in the early part of the 1940-41 season. Again the disagreement between these data and the general trend can be attributed to soil changes occurring just before that rainy season. At that time (the end of the soil settling period) a layer of overfill soil approximately six inches thick was removed from all the large lysimeters. As a result of the removal of the drier top soil, the large lysimeter entered the rainy season with a higher-than-normal average moisture content, while the addition of dry soil to the top of the medium lysimeters reduced their average moisture content. The influence of this treatment persisted until January 1941, when the bare medium lysimeters had almost reached their maximum water content.

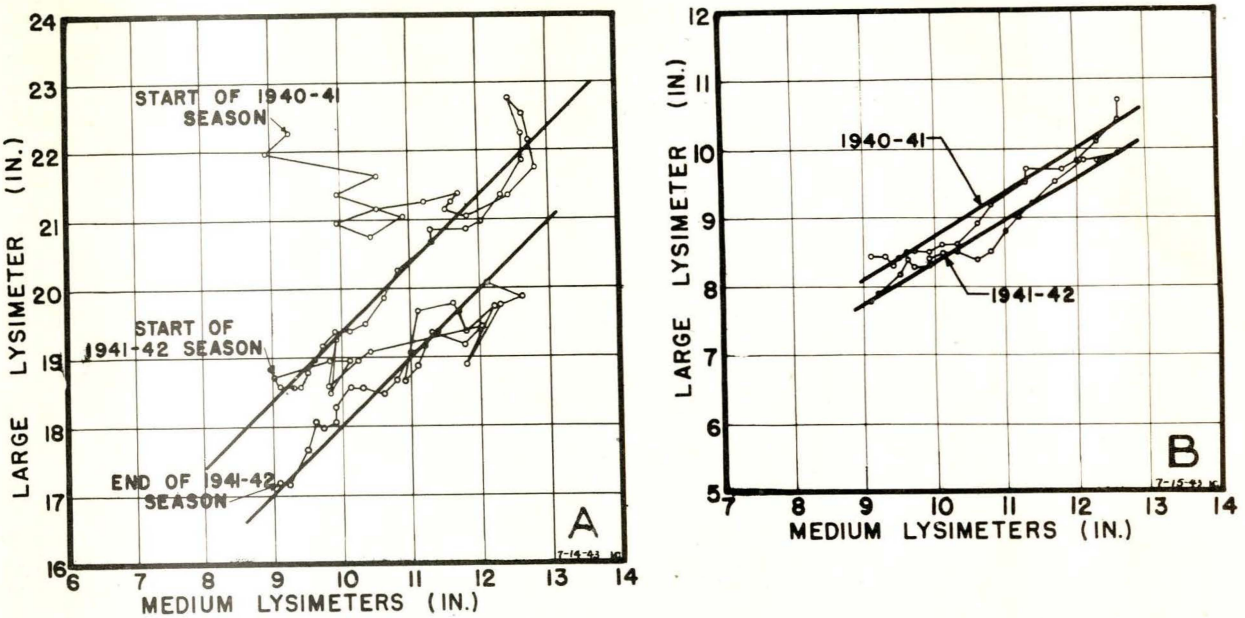


Figure 11.—Relation between water content of bare large and medium lysimeters, 1940-42; (A) Full lysimeter depths, (B) 38-inch soil depths during dry seasons.

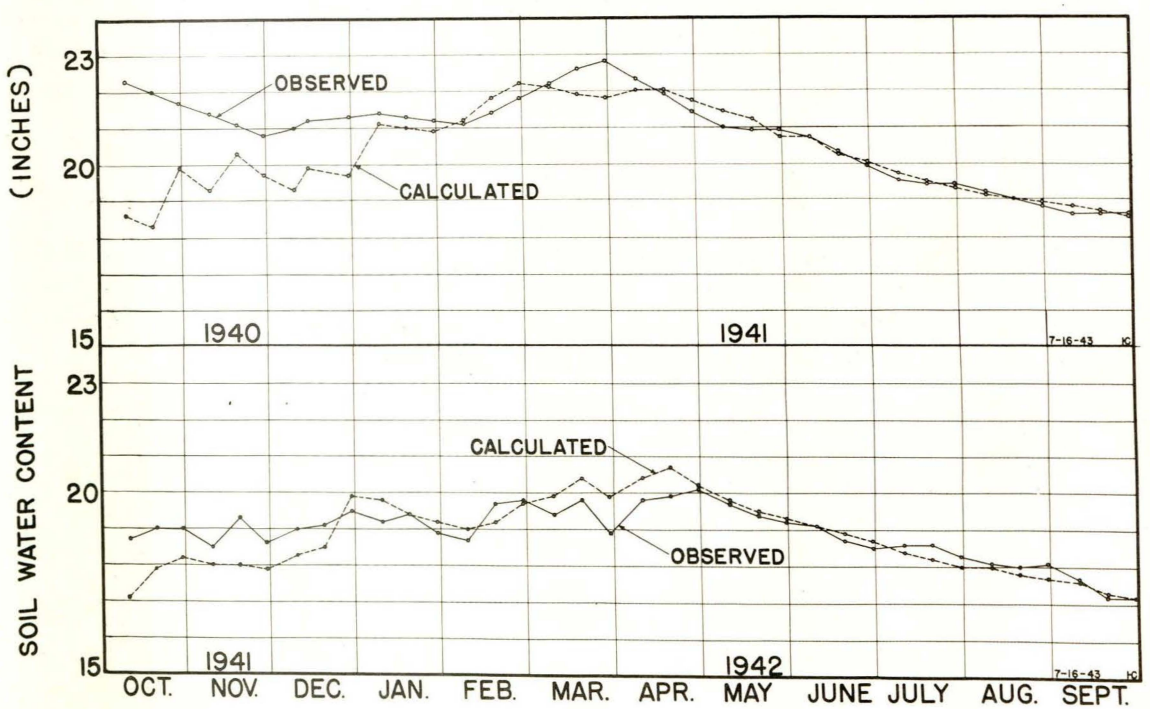


Figure 12.—Observed and calculated soil-water cycles in the bare large lysimeter, 1940-42.

The equal dry-season water losses in the bare medium and large lysimeters are probably something of a coincidence, for all the water lost from the large lysimeters did not come from the top 38 inches of soil corresponding to the medium lysimeter soil-depth. This may be seen by reference to Figure 11(B), in which the water content of the top 38 inches of large-lysimeter soil has been shown in relation to that of the medium lysimeters at corresponding dates. If all the water loss from the large lysimeter had come from above 38 inches depth, the slope of the regression line in this figure would have been equal to that in Figure 11(A). Actually, however, only two-thirds as much water was lost from 38 inches of soil in the large lysimeter as from the corresponding depth of soil in the medium lysimeter. The remaining one-third of the water lost must have come from greater depths in the large lysimeter, so that its evaporation loss during the dry season was equal to that of the medium lysimeters.

The relations derived in Figure 11(A) have been applied in Figure 12, where the observed water content of the bare large lysimeter at any date can be compared with that calculated from the water content of the bare medium lysimeter by the use of the equations given above. The agreement of the two amounts is rather poor during that portion of each year when the soil moisture content is high, but it becomes very good during the drying seasons.

The fundamental difference between these lysimeters seems to arise from the incomplete moisture recharge of the large lysimeters during one of the two years studied, a condition not encountered in the medium lysimeters. It appears probable that both lysimeters would have had closely related water cycles, regardless of their surface areas, if both had had the same soil depth and equal freedom of surface drainage.

Relationship between water contents of large and medium lysimeters supporting a cover of annual grass.

When medium and large lysimeters having a grass cover are compared (fig. 13) the resulting relation is more indefinite than the one between the bare lysimeters. The curved regression line in Figure 13 is based upon all data except that of the early part of the 1940-41 season, which was unique because of the removal of soil from the surface of the large lysimeters. Although a curvilinear relation is indicated, the scatter of the data about the regression line detracts from the significance of its location and shape. The relation is not improved by a comparison of the water contents of the 38-inch deep soil layers alone. Consequently these data have not been included here.

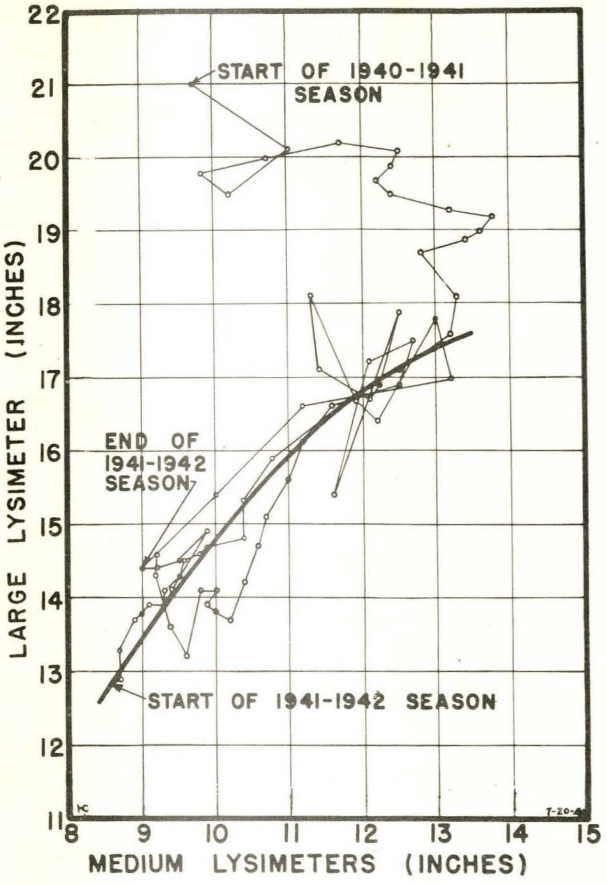
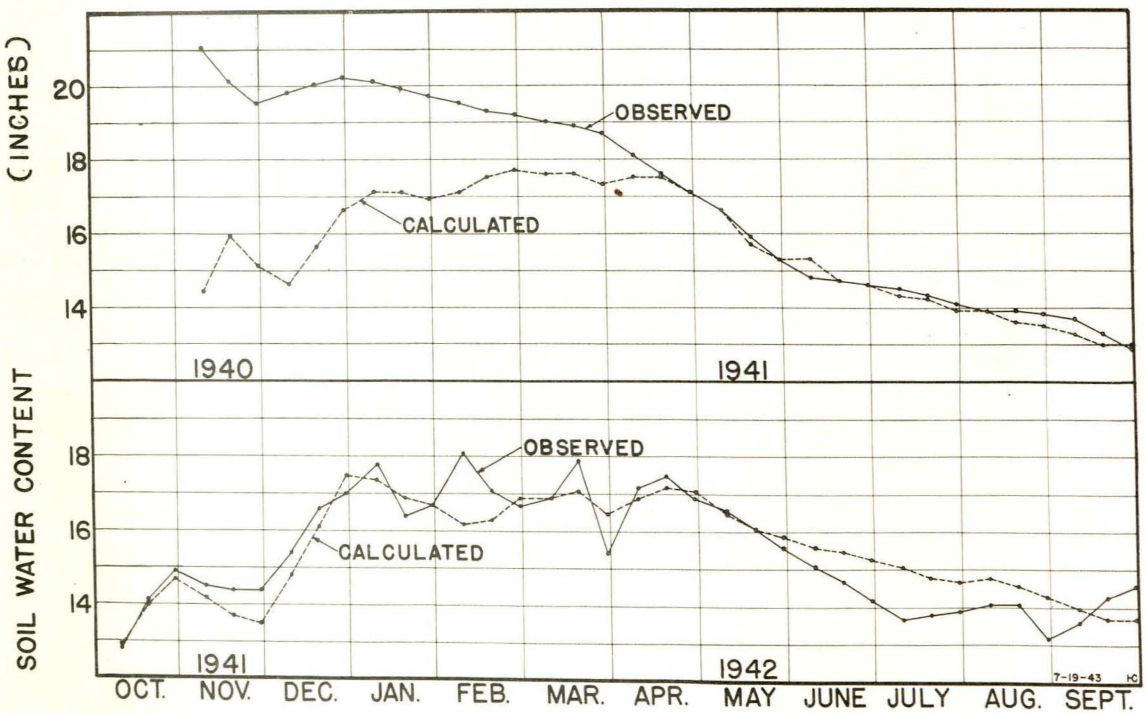


Figure 13.—Relation between water content of grass-covered large and medium lysimeters, 1940-42.

Figure 14.—Observed and calculated soil-water cycles in grass-covered large lysimeters, 1940-42.



Application of the regression curve to the observed water-content data is made in Figure 14. As was to be expected, the early part of the 1940-41 season shows poor agreement between observed and calculated values. The later part of this season shows good general agreement. The next season exhibits fair agreement during the earlier part of the year, but the water-loss rates measured in the large lysimeter during the later part of the year are considerably greater than those indicated by the calculated water-content line. These results indicate that the grass-covered medium and large lysimeters are comparable as to their water losses only in the most general way.

Reasons for the lack of consistent relationships between these lysimeters may be traced to the yield of grass (to be discussed later), and to their uptake and storage of water. Differences in water absorption between the large and medium lysimeters have already been explained. Summer water losses from the grass-covered large lysimeters were 5.6 inches in 1941 and 4.3 inches in 1942, compared with losses of 4.9 inches and 3.6 inches respectively from the medium lysimeters. It follows that, although only the grass-covered medium lysimeters produced seepage each year, they lost less water by evaporation than did the large ones. The greater soil depth and better conditions for root development in the large lysimeters (see discussion of grass yield) appear to have resulted in heavier grass yield with increased evapo-transpirational water use relative to that of the medium lysimeters. On the basis of this analysis it cannot be said that a unique relation does exist or would be expected to exist between the medium and large grass-covered lysimeters.

Relation between water content of large and unconfined lysimeters, and between that of medium and unconfined lysimeters.

The water contents of the grass-covered large lysimeters are compared in Figure 15 with the water content of the grass-covered unconfined lysimeters at corresponding dates. Figure 16 presents the same relation between the medium and unconfined lysimeters. Both graphs show a wide scatter of points and no consistent relation through the two-year period. Therefore, no attempt has been made to establish a regression line relating these lysimeters. Although both reached approximately the same maximum values in the 1940-41 season, the rate of water loss from the unconfined lysimeters during the early summer was by far the greater. The low rainfall of the next season did not permit complete recharge of moisture storage in either lysimeter, and the rates of water loss from the two lysimeters during the early summer of 1942 were nearly equal. However, even under these conditions the soil water contents of the two lysimeter groups cannot be considered to be uniquely related. A comparison of Figure 17 with Figure 9 shows also the lack of a unique relationship between unconfined and medium lysimeters planted with the same kind of vegetation.

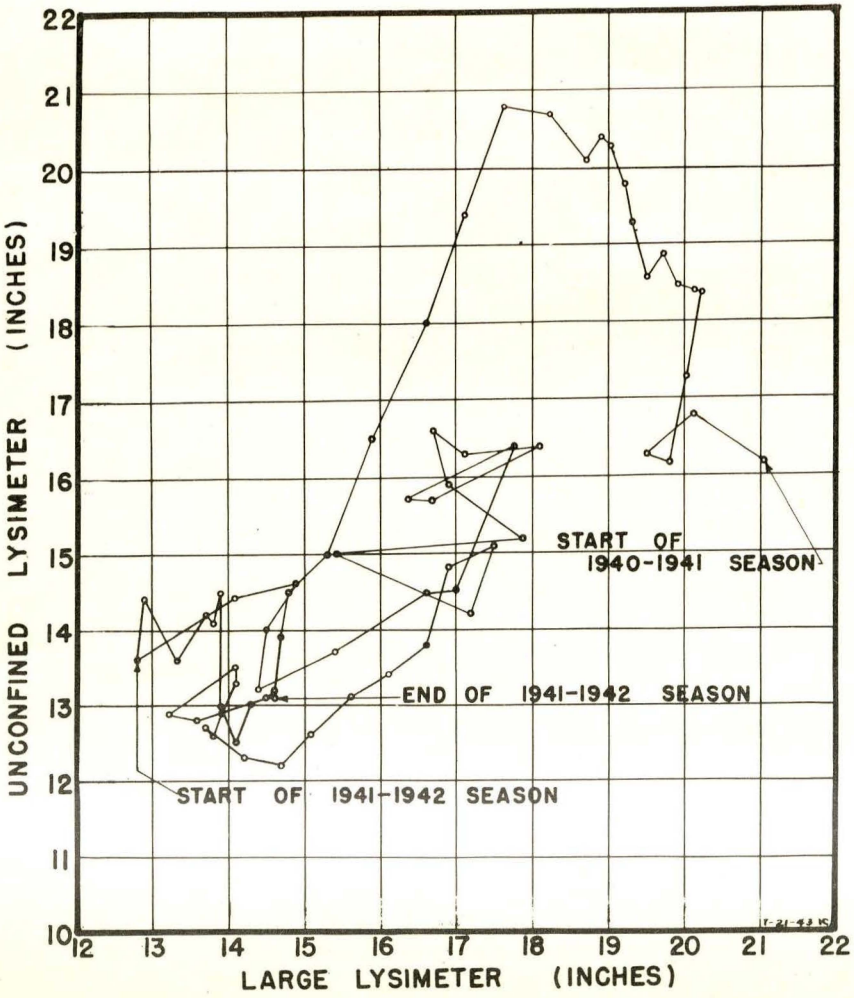


Figure 15.—Relation between water content of grass-covered unconfined and large lysimeters, 1940-42.

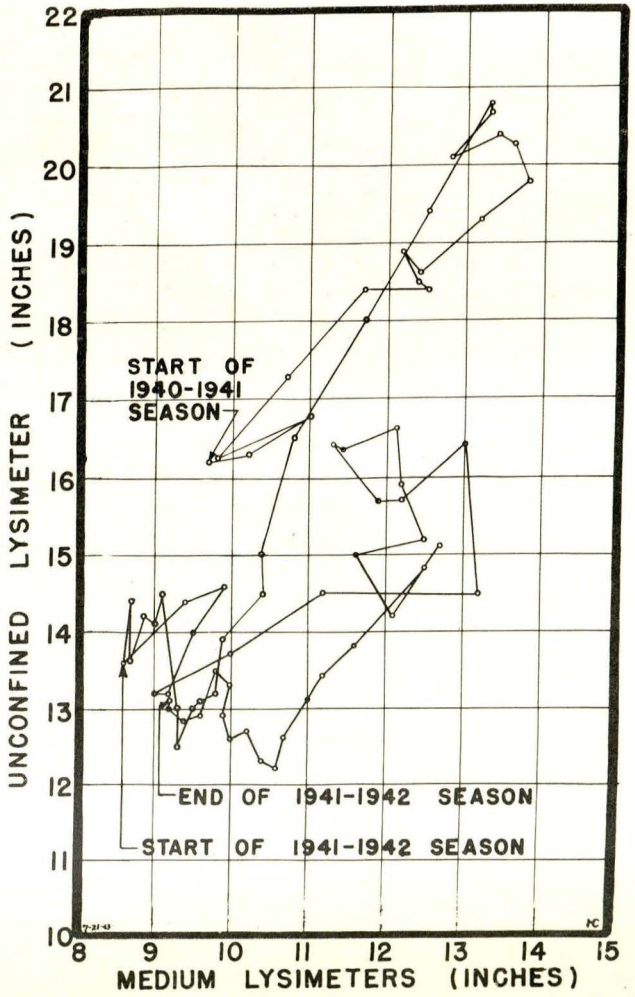


Figure 16.—Relation between water content of grass-covered unconfined and medium lysimeters, 1940-42.

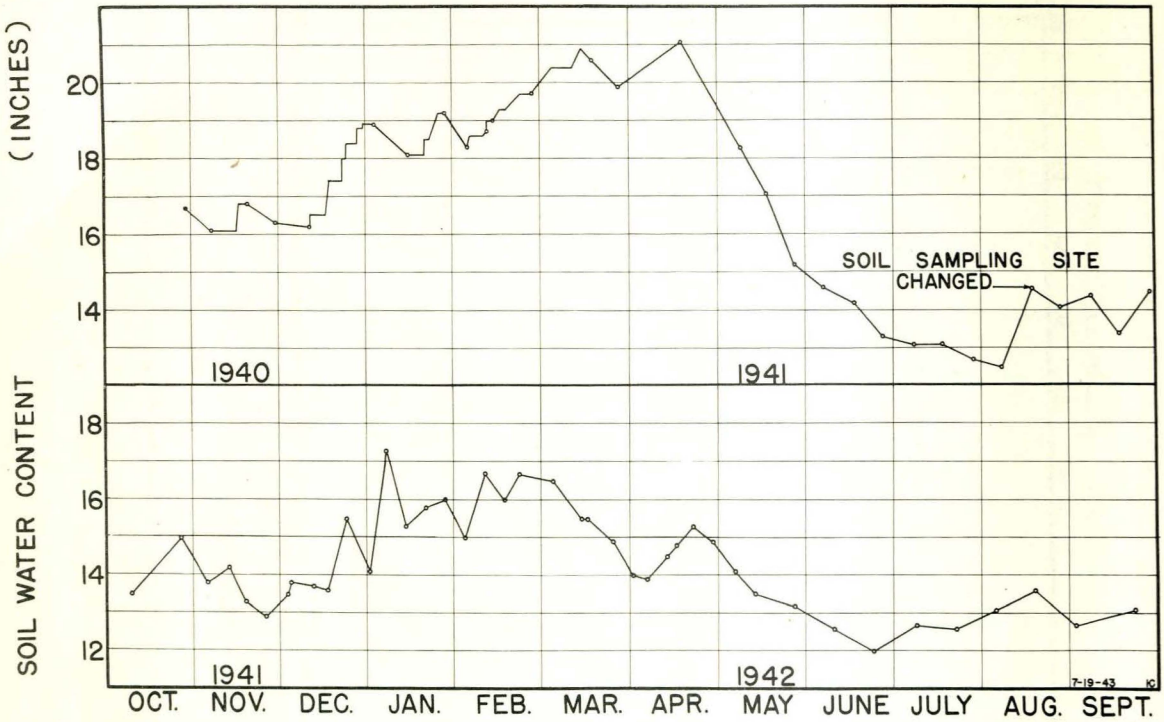


Figure 17.—Observed soil-water cycles in grass-covered unconfined lysimeter, 1940-42.

The lack of a soil/air interface at the base of the unconfined lysimeter introduces a fundamental difference between this kind of lysimeter and the enclosed soil blocks represented by the large, medium, and small lysimeters. Seepage water in the large lysimeters can be lost from the soil only by its passage into the drain pipe at the lower edge of the soil block. Hence, seepage from these lysimeters continues long after tensiometer measurements in the bottom of the unconfined soil blocks have shown that downward movement has ceased. Furthermore, tensiometers in the soil at the base of the large lysimeters show that the soil moisture tension there must equal zero before seepage will start, while tensions of 3 to 5 cm. of mercury have been measured regularly by tensiometers at the base of the unconfined lysimeters during their seepage period.

These last observations indicate that the maximum soil moistures in the unconfined lysimeters are definitely below saturation while those near the base of the large lysimeters are representative of a saturated condition. The resulting better aeration of the unconfined lysimeters may be the cause of their greater crop yield (see grass yield discussion) and evapo-transpiration water loss in the 1940-41 season, as shown in Table 3. The reversal shown in this table for the 1941-42 season is probably due to the lower soil moisture contents of both these lysimeters (resulting in better soil aeration) caused by the deficient and sporadic rainfall of this year.

The conclusion must be drawn that the unconfined lysimeters bear no consistent relation to the other lysimeter groups insofar as their water contents and water losses are concerned.

Table 3. Evapo-transpiration water loss during the dry seasons of 1941 and 1942, in the large and unconfined lysimeters

Year	Season	Water loss	
		Large lysimeter	Unconfined lysimeter
		Inches	Inches
1940-41	April to October	5.6	9.0
1941-42	May to September	4.3	2.4

Grass yields in the lysimeter groups.

The annual harvest of grass (Bromus mollis) on the lysimeters made it possible to obtain direct comparisons of grass yield per unit area of lysimeter surface. These data demonstrate the striking differences in growing conditions in the several lysimeter groups (table 4). The fairly good agreement between large and unconfined lysimeter yields stands in marked contrast to the lower yields from the shallower soil tanks. That the differences are not caused by limited water supply in the smaller tanks has been established by soil moisture determinations made in the lysimeters after the grass had matured and dried. In no case did the average moisture content approach the wilting point of the soil. Although scarcity of water was not the cause of lower grass yields in the shallower lysimeters, it appears possible that periods of excess water during the growing season may have been. The small and medium lysimeters produced seepage during 1941 and 1942 and free water was often observed on the soil surfaces of the small lysimeters after periods of rain. It appears probable that, owing to the interface conditions at the base of the soil columns, the small lysimeters may be nearly saturated through the greater part of their 24-inch depth before seepage takes place. By the same token the medium and large lysimeters would be saturated to an equal height above the seepage plane. This would provide a greater depth of aerated soil with increasing depth of lysimeter. Thus, the deeper the soil block, under these drainage conditions, the better would be the average growing condition for plants.

Table 4.- Annual grass yield of San Dimas lysimeters

Lysimeter type	No.	Average yield (oven dry) 1940-41		1941-42	
		lb/sq.ft.	lb/acre	lb/sq.ft.	lb/acre
Unconfined	5	.088	3500	.026	1130
Large	25	.069	3100	.026	1130
Medium	26	.029	1260	.009	392
Small	68	.013	566	.009	392

Soil moisture samples taken in the large lysimeters during their seepage period in 1943 revealed that only within the top foot was the soil significantly drier than that at corresponding depths in the medium and small lysimeters. It may be that the differences in plant growth depend upon these observed top-soil differences. Soil sampling has not provided a basis upon which to judge the significance of yield differences between large and unconfined lysimeters. However, a comparison of the soil water content curves of the large and unconfined lysimeters (figs. 9 and 12) during the late spring of 1941 shows a far greater rate of moisture loss from the latter. This probably implies better growing conditions in the unconfined lysimeters, since the average water content of the two lysimeters was essentially the same. The almost equal rates of water loss from these two lysimeters noted during the corresponding period of the next year, coupled with the generally lower moistures which prevailed that year, may explain the equality of yield in the 1942 harvest.

Thus it is shown that, at least under conditions of complete annual recharge of soil moisture, the yield of annual grass diminishes progressively in the sequence: unconfined, large, medium, and small lysimeters (table 4). Under these conditions none of the lysimeter groups can be said to be producing comparable data and all three groups of enclosed lysimeters produce lower yields than do the most naturally exposed soil blocks, the unconfined lysimeters.

CONCLUSIONS

1. Under conditions of purely evaporative soil moisture loss or under a light cover of annual grass there is a close linear relation between the water content of the small and medium lysimeters. Over the period of study one set of constants for bare and one for grass-covered lysimeters has satisfied this relation. However, the same constants do not relate the two lysimeter groups under different treatments, showing that the method of handling the lysimeters influences the relation existing between them. It is suggested that the consistent relation found between small and medium lysimeters is the result of two causes: the complete moisture recharge of both each year, and the failure of evaporation and transpiration to reduce these soils to their wilting points.

If chaparral or other perennial vegetation were growing in these lysimeters, it is anticipated that the available water would be exhausted more rapidly in the small than in the medium lysimeters. Under these conditions it may be that the equation relating the two would be less simple and less significant.

2. Although a simple relation appears to exist between the water contents of the bare large and medium lysimeters during the dry season, the same relation does not hold for successive years. Nor does the summer relation hold during the rainy season. The relation between grass-covered lysimeters is only very general at any time. The inconsistencies brought out above show that the medium lysimeters cannot be considered to be models of the large ones and that in this case, as well as in that of the medium and small lysimeters, the treatment of the lysimeters has a considerable influence on the relation existing between them.

3. The unconfined lysimeters show no consistent relation to any of the other lysimeter types so far as the water regime is concerned. In grass yield, however, they are closely approximated by the large lysimeters. The unconfined lysimeters are fundamentally different from the others in that seepage from them is unobstructed while a soil/air interface is present in the other lysimeters. It appears probable that this difference in seepage condition has led to significantly different moisture distributions and growing conditions between the unconfined and other lysimeter groups.

IMPROVEMENTS IN LYSIMETER DESIGN

It is recognized that the unconfined lysimeters present conditions more closely approaching those in field soils than do any of the other lysimeters. The fact that the water losses from the other lysimeters do not agree with these implies short-comings in the design of the small, medium and large lysimeters. These short-comings are thought to exist in the form of: 1. the soil-over-air seepage interface; 2. too shallow a soil layer in medium and small lysimeters; and, 3. restricted surface runoff in medium and small lysimeters. As a result, too much water has entered the medium and small lysimeters, poorly aerated soil has led to subnormal plant growth, and inconsistent relations of evaporation and evapo-transpiration water losses have developed between the several types of lysimeters.

Improvements in the San Dimas installation involve providing for (a) complete surface drainage and extension of the soil depths in the medium and small lysimeters to the six-foot depth provided in the large ones and (b) modification of seepage conditions in all the enclosed soil blocks with a view toward minimizing the abnormal moisture conditions now prevailing. The method of accomplishing the last-mentioned improvement was made the subject of a recent study (3). This study demonstrated that excess water can be drained from a lysimeter by placing fine-pored fired-clay tubes in the lower part of the soil block and maintaining a moisture tension in the pores equal to that found in the soil at field capacity. The equipment required to perform this drainage function is not complicated in form or operation. It requires, however, special design and manufacture, and careful installation.

SUMMARY

Comparisons of the soil water cycle, annual evapo-transpiration values, and yield of annual grass, have been made between four types of lysimeters which are included in the San Dimas lysimeter installation. These lysimeters exhibit differences in depth, size, surface drainage, and seepage conditions. Some have been maintained bare and some have supported stands of Bromus mollis.

A unique relation was found to exist between the water content of cylindrical lysimeters 24 and 38 inches deep permitting the water content of one to be calculated at any time from that measured in the other. A somewhat less definite relation was found between these and the third type, a concrete box six feet in depth. Finally no unique relation was found between the enclosed, box-type lysimeter and six-foot-deep pits filled with the same kind of soil. This latter "unconfined" lysimeter differed from the others in permitting seepage unobstructed by the soil/air seepage interface which caused the development of a saturated soil layer above the seepage plane of the other lysimeters.

Grass yields became progressively lower as soil depth decreased, not as a result of water lack, but more probably stemming from the poor aeration of the shallow soil blocks arising from the saturated soil present within their lower depths.

Since the "unconfined" lysimeters are the most nearly natural of the lysimeter types, improvements in lysimeter design should seek duplication of conditions within them. It is proposed that this can be accomplished by (1) increasing the depths of all soil blocks to six feet; (2) providing complete surface drainage; and (3) eliminating abnormal soil moisture condition by removal of the soil/air seepage interfaces.

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